



**CARBON
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Ready Mix Technology Case Studies



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Ready mix concrete producers in the United States, Canada and Singapore are using the CarbonCure Ready Mix Technology to adjust their concrete mix designs. The compressive strength improvements from an optimized injection of CO₂ enable the production of concrete without sacrificing performance or durability. Since being introduced commercially, more than 4 million cubic yards of concrete have been produced with the CarbonCure Technology, achieving material savings and avoiding CO₂ emissions that exceed 63,000 tons as of January 2020.

EXECUTIVE SUMMARY

The CarbonCure Ready Mix Concrete Technology is being implemented by concrete producers across the United States and Canada to improve the compressive strength and environmental footprint of their concrete products. This case study examines data provided by a CarbonCure producer partner who installed the CarbonCure technology and used the system to produce concrete with an optimized dosage of CO₂.

Concrete prepared using the CO₂ injection system was shown to deliver comparable compressive strength performance with a 5-8% reduction in binder loading while having a neutral impact on fresh properties, including air, slump, and temperature. Roughly 45 000 yd³ of concrete were produced over an 10 month period using a 5% binder reduction in conjunction with an optimized dose of CO₂. The estimated cement savings exceeded 600 tons and more than 550 tons of CO₂ emissions were avoided. The use of the technology did not impact the producer's cycle time; all operations continued as normal throughout this assessment.

The action of the CO₂ is discussed in terms of nanomaterial impacts. The injection of carbon dioxide into the concrete mix forms well dispersed calcium carbonate nanoparticles, which allows concrete producers to realize the understood benefits of nanoparticle additions while avoiding common technical or economic barriers. The technology delivers value to the concrete producer while reducing the concrete's environmental impact.

Introduction

This case study analyzes data collected by a CarbonCure producer utilizing the CarbonCure Ready Mix Technology to inject CO₂ during normal concrete operations. The CarbonCure technology controlled the carbon dioxide delivery into the ready mix concrete truck during the initial batching and mixing. The carbon dioxide was bound as solid and stable carbonate reaction products in the cement matrix and provided a positive impact on the concrete properties.

Methods

The fresh concrete was assessed via on-site measurement of slump, temperature, air content and unit weight. The concrete was then cast into 4" x 8" cylinders for compressive strength testing at 7, 14 and 28 days after batching. All concrete specimens were prepared and tested in accordance with the relevant ASTM and ACI standards.

The CarbonCure Ready Mix Technology controlled the delivery of CO₂ into the concrete. In a process that resembles the introduction of a chemical admixture, a tank of liquid CO₂ was connected to the CarbonCure injection system. The liquid was metered to deliver an optimum dose of CO₂ into the drum of the ready mix truck at the same time as the concrete was loaded. Upon entering the mixing drum, the liquid carbon dioxide converted into a mixture of CO₂ gas and solid carbon dioxide snow whereupon it reacted with the hydrating cement to form solid

calcium carbonate particles. The concrete was then subjected to assessment and testing.

All samples were collected from trucks carrying 9 yd³ of a residential mix with design strength of 3000 psi. The concrete mix design used a ternary binder system of Portland cement, class F fly ash and slag.

To illustrate the potential of CO₂ in mix design optimization, a three-way comparison was conducted between a standard mix, a mix with reduced binder content, and a reduced binder mix that used an optimized dose of CO₂. Two mix designs, including/excluding air entrainment admixtures, were examined. The relevant binder loadings for the mix designs are summarised in Table 1. Small adjustments of fine aggregate loadings were also included to ensure that yield was maintained following a reduction in binder loading.

The binder reduction leads to a decrease in paste volume, but can also serve to slightly increase the water to cementitious ratio and admix loading per unit of binder. The former is expected to have a negative impact on strength development while the latter is expected to have a neutral impact.

Strength Enhancement Results

An overview of the fresh properties for the loads produced during the production run is presented in Table 2.

Table 1: Binder loadings for four mix design variations.

Mix Type	Type	Cement (lbs/yd ³)			
			Class F Fly Ash (lbs/yd ³)	Slag (lbs/yd ³)	Total Binder (lbs/yd ³)
	Standard Mix				
Non Air Entrained	Reduced Binder	258	132	149	539
	Mix Relative	249	132	119	500
	Change	-4%	n/a	-20%	-7%
Air Entrained	Reduced Binder	281	109	151	540
	Mix Relative	248	129	119	496
	Change	-12%	+18%	-21%	-8%

Table 2: Production variables, CO₂ settings and fresh results.

Mix	Type	Slump (in)	Air (%)	Unit Wt (lbs/ft ³)	Temp (°F)
Non Air Entrained	Reduced Binder	5	2.5	146.6	84
	Reduced Binder with CO ₂ Standard Mix	4	2.5	147.2	84
	CO ₂ Standard Mix	4	2.5	147.2	84
Air Entrained	Reduced Binder	6	4.2	144.4	84
	Reduced Binder with CO ₂ Standard Mix	5	3.4	147.2	81
	CO ₂ Standard Mix	6	3.5	146.0	84

The average compressive strength measured for each batch at three test ages is summarized in Figure 1.

The binder modification in the non-air entrained batch lead a strength reduction at all ages including a 17% drop in 28 day compressive strength. However, when the carbon dioxide was added the strength of the reduced binder batch improved to be within 4% of the reference at 28 days. The trial represented the first attempt at an optimized mix design and it was observed that further tweaks of the modified mix

design and/or CO₂ dose should establish that the CO₂ addition can result in at least equivalent performance at all ages. The 28 day data suggested that a CO₂ injection in conjunction with a binder reduction on the order of 7% can create concrete without compromising performance.

The binder reduction in the air entrained batch lead to an 11-13% drop in compressive strength across the three test ages.

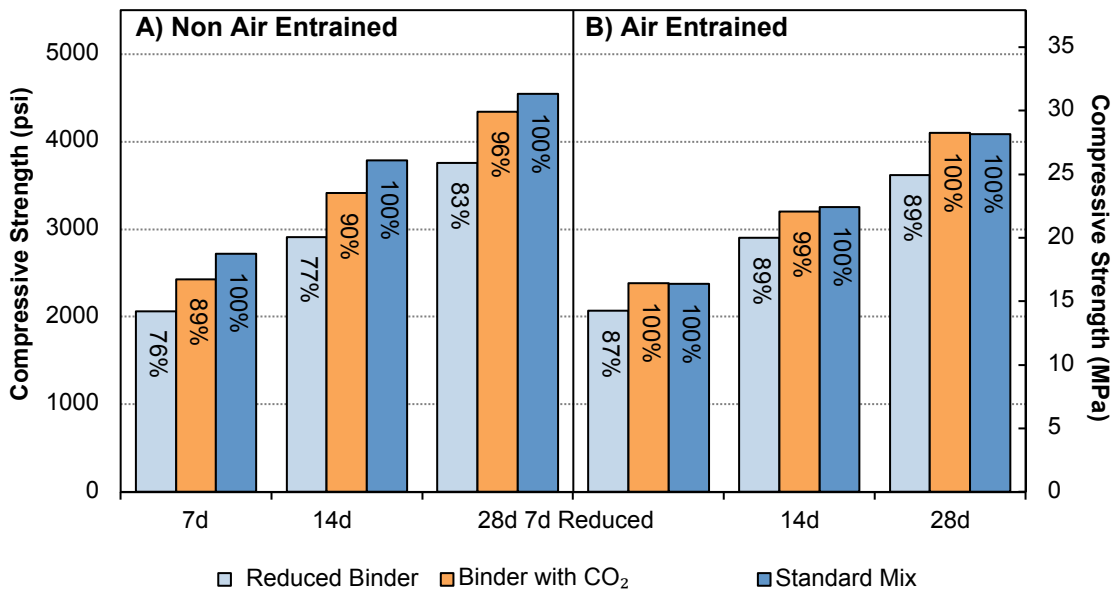


Figure 1: Compressive strength development of non air entrained (A) and air entrained (B) concrete test loads. For each mix the customer compared 3 cases: A standard mix (dark blue), the standard mix with a reduction in binder loading (light blue), and the standard mix with a reduction in binder loading that further incorporated the addition of an optimized dose of CO₂ (orange). The binder reductions were 8% and 7% for the non air entrained and air entrained variations respectively.

However, when the carbon dioxide was added the strength of the reduced binder batch improved to be equivalent to the standard mix.

The strength benefit results confirmed two major outcomes:

- 1) A reduction in the binder loading leads to a reduction in the compressive strength
- 2) The strength reduction could be offset through the introduction of CO₂ into the concrete mix during batching

The conclusion was examined in extended production.

Extended Production Results

Three mix designs were selected for expanded testing to assess the performance enhancement of CO₂ across a range of concrete strength classes. The compressive strength development of mixes with 28 day design strengths of 3000, 5500 and 8000 psi were assessed when using CO₂ alongside reductions in binder loading of 4.5%, 4.4% and 3.1% respectively. The 7 and 28 day compressive strength results for each mix design are plotted in Figures 2-4 against graphical ranges of historical data

representing the average, 10th percentile and 90th percentile results for the unmodified mix.

In each case the addition of an optimized dosage of CO₂ was shown to bring the performance of the concrete mix design with a reduced binder loading within the expected performance range based on historical data. The average and the variation of the reduced binder CO₂ batches were consistent with the historical data of the unmodified mix. The acceptable production of batches using the CO₂ and a reduced binder loading across a range of strength classes was assured.

The success of these two assessments encouraged the ready mix concrete producer to apply the CarbonCure Ready Mix Concrete Technology across their concrete production. Over a 10-month period, spanning March to December, CO₂ was injected into roughly 56,000 yd³ of concrete with an average cement reduction of 5%. The extended implementation of the technology resulted in 600 tons of cement savings and, according to emissions information specific to the cement, 530 tons of avoided CO₂ emissions (Figure 5).

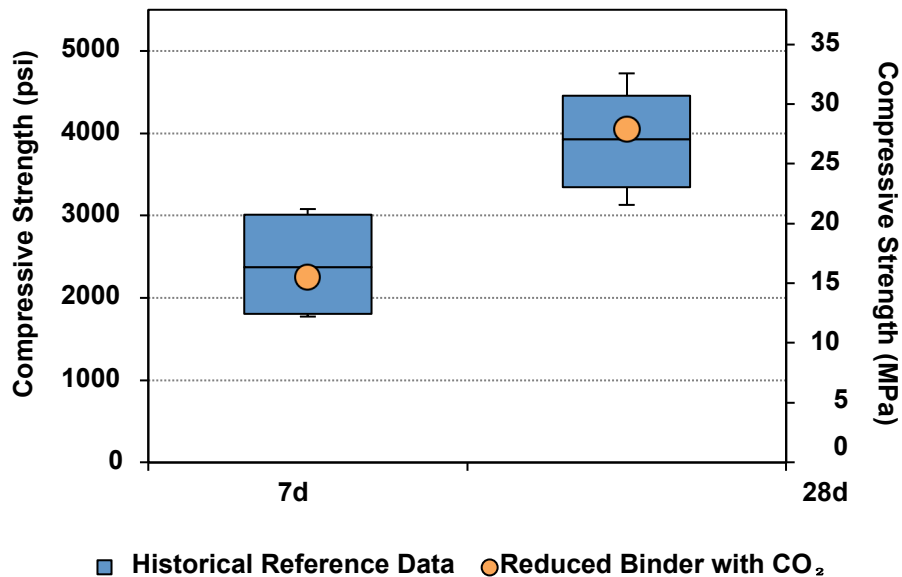


Figure 2: Compressive strength development of a 3000 psi air entrained mix. The blue boxes represent the historical compressive strength performance range (10th to 90th percentile) while the orange circles represent the compressive strengths of loads of the mix prepared with a 4.3% reduction in binder content (5.7% reduction in cement content) and an optimized dose of CO₂. Whiskers indicate the historical data maximum and minimums.

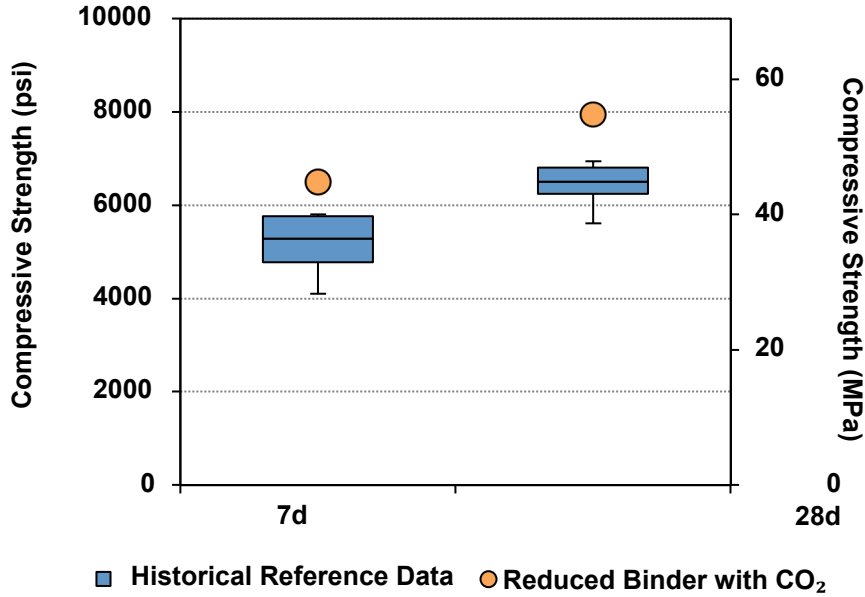


Figure 3: Compressive strength development of a 5500 psi mix designed for high early strength applications. The blue boxes represent the historical compressive strength performance range (10th to 90th percentile) while the orange circles represent the compressive strengths of loads of the mix prepared with a 4.4% reduction in binder content (4.4% reduction in cement content) and an optimized dose of CO₂. Whiskers indicate the historical data maximum and minimums.

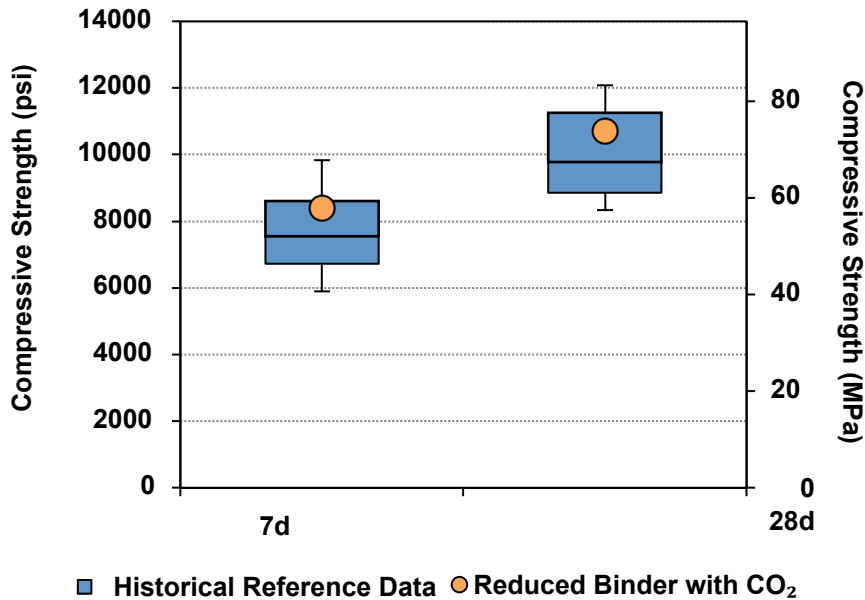


Figure 4: Compressive strength development of an 8000 psi mix. The blue boxes represent the historical compressive strength performance range (10th to 90th percentile) while the orange circles represent the compressive strengths of loads of the mix prepared with a 3.1% reduction in binder content (6.0% reduction in cement content) and an optimized dose of CO₂. Whiskers indicate the historical data maximum and minimums.

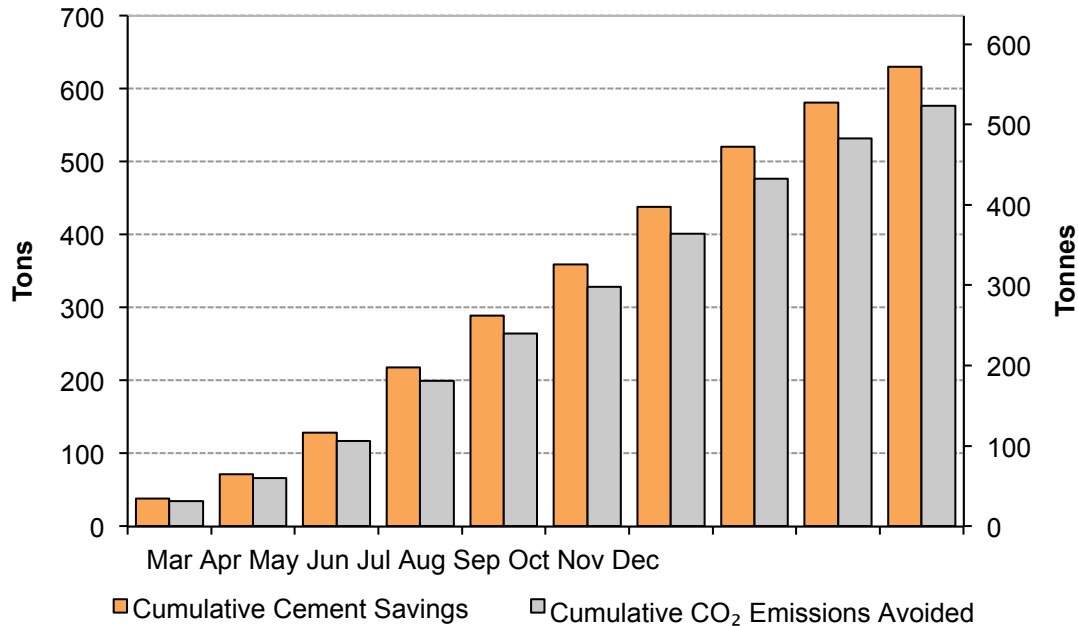


Figure 5: Cumulative cement savings (orange) and avoided CO₂ emissions (gray) for a producer using the CarbonCure Ready Mix Technology in conjunction with a 5% cement reduction over an 10 month period. These reductions were totalled through the production of approximately 56 000 yd³ of concrete.

This customer data provides verification that producers can leverage the strength enhancing effect of the CO₂ to achieve binder adjustments with diverse motivations:

- Economic – reducing the overall amount of binder can save money. The reduction of the most expensive components can be prioritized.
- Performance – durability benefits related to increased binder proportioning of slag and/or fly ash can be targeted while not compromising on the early strength development.
- Environmental – reducing cement usage directly leads to avoiding CO₂ emissions thereby allowing for a reduction in the carbon footprint of the mix.

Mechanism

When liquefied CO₂ is injected into wet concrete the CO₂ chemically reacts with calcium ions released from cement to form solid, nano-sized calcium carbonate particles that become permanently bound within the concrete.

The main cement phases, tricalcium silicate and dicalcium silicate, are known to react with carbon dioxide in the presence of water to form calcium carbonate¹. The reaction proceeds in the aqueous state when calcium ions from the cementitious phases meet carbonate ions from the applied CO₂.

The reaction of carbon dioxide with hardened concrete is conventionally acknowledged to be a durability issue due to such effects such as shrinkage, reduced pore solution pH, and carbonation induced corrosion. In contrast, carbon dioxide utilization in concrete production reacts CO₂ with freshly hydrating cement, rather than the hydration phases present in mature concrete, and does not have the same effects. Consequently durability is not affected². By virtue of adding CO₂ to freshly mixing concrete the carbonate reaction products are formed within the concrete mix at the nano-scale and homogeneously distributed. Figure 6 shows an example of a nano-scale reaction product formed following the introduction of CO₂ into a hydrating cement sample produced in an associated laboratory test.

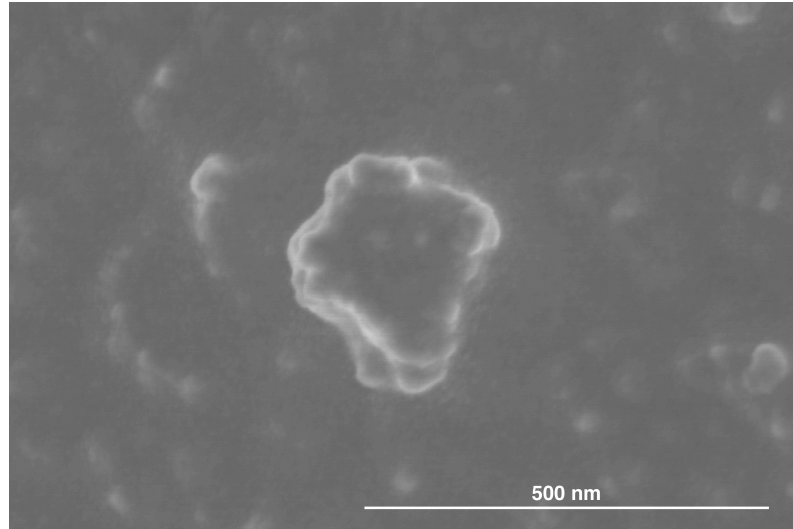


Figure 6: Nano-scale (100-150 nm) calcium carbonate reaction products produced through carbonating freshly hydrating cement as imaged by scanning electron microscopy.

While it is known that the addition of nano-sized calcium carbonate particles can be used to impact the hydration of cement³, concrete producers attempting to add nanoparticles to a concrete mix often run into technical (e.g. difficulty achieving homogeneous dispersion), operational (e.g. availability and/or quality of supply) and economic (e.g. cost) barriers⁴. The addition of liquefied CO₂ injected into the concrete mix enables concrete producers to manufacture nano-CaCO₃ within the concrete mixture at the time of production, thus permitting the producer to realize the benefits of nano-CaCO₃ while avoiding these common barriers.

Conclusions

Industrial scale integration of the CarbonCure ready mix concrete system into a concrete production environment has demonstrated the ability to leverage CO₂ as a new tool in mix design optimization. By combining the strength enhancing

properties of an optimized dose of CO₂ with reduced binder loadings concrete producers are able to achieve equivalent 28-day compressive strength performance with a reduced environmental footprint.

References

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